



Evaluating the benefits of SWOT data assimilation and implications for future operational oceanography

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Abstract.

We present the first evaluation of SWOT data assimilation in a high-resolution ocean forecasting system at the global scale under operational conditions. Observing System Experiments performed with the Mercator Ocean operational data assimilation system are used to assess the gain in model performance associated with the assimilation of SWOT observations into Copernicus Marine Service products. We find that SWOT assimilation improves the global representation of sea level anomaly (SLA), particularly at spatial scales below 100 km. The global gain is of the order of 4%, which is lower than those reported in previous studies, likely reflecting the strong constraint provided by the numerous nadir altimeters already assimilated in the system. Independent validation using drifters deployed during the SWOT Cal/Val phase shows improvements in both the zonal and meridional current components, highlighting the ability of wide-swath observations to provide a more balanced constraint on surface circulation than conventional nadir altimetry. Assimilation experiments with data from both the high-frequency Cal/Val and spatially extensive Science phases show that broader spatial coverage provides a larger global benefit than higher revisit frequency. Experiments with two model configurations further show that the higher-resolution model, which resolves more physical processes, derives greater benefits from SWOT data assimilation. These results provide guidance for the future development of operational oceanography based on wide-swath altimetry, highlighting the need for broader and more frequent satellite sampling, higher-resolution models with improved physical representation, and data assimilation methods adapted to dense, high-resolution, two-dimensional observations.

1 Introduction

For more than two decades, operational oceanography has provided increasingly accurate estimates of the ocean state, from the surface to the deep ocean and from the regional to the global scale (Bell et al., 2009; Le Traon et al., 2015). As such, ocean model products have contributed to a broad range of applications, including in environmental monitoring (e.g. climate and ecosystem monitoring), societal needs (e.g. maritime safety and hazard prevention) and economic activities (e.g. fisheries management and navigation, Rayner et al., 2019). Among the observing systems supporting operational oceanography, altimetry missions have played a key role in advancing ocean forecasting systems by providing global, near-



real-time and all-weather measurements of sea level, which, through data assimilation, provide a strong constraint on 4D ocean circulation (Smedstad et al., 2003; Jacobs et al., 2014; Le Traon et al., 2015; Le Traon et al., 2025).

The launch of SWOT (Surface Water and Ocean Topography) mission in 2022, marked a breakthrough for ocean science (Fu et al., 2024; Morrow et al., 2019). Embarking Ka-band radar interferometer (KaRIn), the first wide-swath altimeter, SWOT delivers two-dimensional maps of the global ocean at an unprecedented resolution of 2 km (Dibarboure et al., 2025). Numerous studies have since demonstrated the accuracy of the satellite and its value across a wide range of oceanographic domains (e.g. Coadou-Chaventon et al., 2025; Dibarboure et al., 2025; Tchonang et al., 2026; Verger-Miralles et al., 2025, Hart-Davis et al., 2026, Jestin et al., 2026). Operational oceanography is one such application, which undergoes transformations with the advent of wide-swath altimetry.

Data assimilation systems have been adapted across the community to address the challenges posed by SWOT's dense spatial sampling, correlated observation errors, and ability to resolve submesoscale dynamics (Carrier et al., 2016; D'Addezio et al., 2026, 2019; Jacobs et al., 2023; Metref et al., 2020, 2019; Sciacca et al., 2025; Souopgui et al., 2020; Benkiran et al., 2021; Tchonang et al., 2024). These methodological developments have been tested through several observing system simulation experiments (OSSEs) with synthetic wide-swath observations, which demonstrated the benefits of assimilating simulated SWOT observations in high-resolution (1 to 6 km) regional configurations. These studies showed improved representation of mesoscale structures, surface currents, and sea surface height (SSH), and have been confirmed by the recent first observing system experiments (OSEs), using real SWOT observations. Verdy et al. (2026), assimilating SWOT Cal/Val data into a 2 km California Current configuration, showed improved mesoscale circulation and an effective constraint extending to ~70 km, finer than conventional altimetry. Kerry et al. (2026), assimilating SWOT data into a 2.5-6 km East Australian Current configuration, found enhanced mesoscale and finer-scale variability, sharper vorticity gradients, and improvements throughout the water column. Wang et al. (2026) separately assimilated the large and fine scale components of SWOT observations in a 1.8 km resolution regional model in the South China Sea and found a substantial reduction in sub-150 km SLA analysis errors by almost 40%.

Mercator Ocean took part in this effort and has been preparing its operational systems to exploit wide-swath altimetry for several years. Bonaduce et al. (2018) conducted the first OSSEs with synthetic SWOT observations in a regional 1/12° configuration over the Iberian-Biscay-Ireland (IBI) region. Benkiran et al. (2021) and Tchonang et al. (2021) then adapted the assimilation system to fully exploit SWOT measurements and carried out OSSEs to assess the impact of SWOT data assimilation, this time, on a global scale. Their study showed that combining SWOT with three conventional nadir altimeters reduced the variance of SSH and surface velocity errors by approximately 30% and 20%, respectively, with the largest gains at wavelengths below 200 km.

Before moving to the assimilation of real SWOT data, Fouchet et al. (2025) compared the physical ocean signals observed by SWOT to those represented by the model, prior to SWOT data assimilation. They found that SWOT and the model agree at large scales but show significant discrepancies at higher frequencies, due to submesoscale signals in SWOT



65 observations that are too small for the model grid resolution or simply not parametrized. This preliminary study paved the way for effectively integrating SWOT data into operational assimilation systems.

Benkiran et al. (2026) then conducted the very first OSEs at the global scale, assessing SWOT real data assimilation in a configuration close to the OSSEs of Tchonang et al. (2021), i.e. with three nadir altimeters only. Their study showed that global SWOT data assimilation improves model estimates of SLA by 18%, as well as the direction and magnitude of surface currents.

70 The study presented here provides the first analysis of OSEs conducted with real SWOT observations, under fully operational conditions and at the global scale. We examine how the Mercator Ocean assimilation system responds to SWOT data assimilation when (almost) all other available observing systems are also assimilated. We thereby assess the impact of SWOT under conditions representative of its future operational use within the Copernicus Marine Service.

To better understand the model response to SWOT data assimilation, we investigate the respective roles of model 75 resolution and satellite sampling. On the one hand, we compare SWOT data assimilation experiments in the global $1/12^\circ$ and the regional IBI $1/36^\circ$ Copernicus Marine Service configurations to assess how model resolution affects the ability to exploit high-resolution wide-swath altimetry. On the other hand, we take advantage of the two SWOT mission phases to examine the response of the assimilation system to different sampling strategies: the high temporal sampling of the Cal/Val phase, with its 1-day repeat orbit, and the extensive spatial coverage of the Science phase. These comparisons are intended to 80 provide insights into both model and observing system requirements, with implications for the design of future altimetry missions and the evolution of ocean forecasting systems.

The paper is organized as follows. Section 2 describes the Mercator Ocean forecasting systems and the SWOT data assimilation experiments; Section 3 assesses the impact of SWOT data assimilation on sea level and surface currents; Section 4 examines the effects of satellite sampling and model configuration; and Section 5 summarizes the main findings 85 and conclusions of this study and discusses their implications for future operational oceanography.

2 Observing system experiments

Mercator Ocean models are based on the NEMO3.6 ocean model (Madec et al., 2017), defined on tripolar grids and using 50 vertical z-coordinate levels. They rely on the SAM2 (Système d'Assimilation Mercator, version 2) data assimilation system, which combines a 3D-Var scheme to correct slowly evolving large-scale temperature and salinity biases with a local 90 reduced-order Kalman filter building on the Singular Evolutive Extended Kalman Filter (SEEK) formulation. It consists of a sequential scheme composed of a forecast step, followed by an analysis step using a 7-day assimilation window. The resulting analysis increments are then progressively applied to the numerical model using an Incremental Analysis Update (IAU) scheme. This approach is fully described in Lellouche et al. (2018). Prior to SWOT launch, the data assimilation scheme has been updated to take full advantage of SWOT KaRIn data, including a different parametrisation of the model



95 error covariance and the use of a four-dimensional version of the data assimilation scheme. These updates are described in Benkiran et al. (2021) and assessed with OSSEs presented in Tchonang et al. (2021).

The experiments presented here are close to the operational conditions: we assimilate all available operational observing systems, including temperature and salinity vertical profiles from the Copernicus Marine In Situ Thematic Assembly Centres (TACs), L3 satellite sea surface temperature (SST) from the Copernicus Marine ODYSSEA product
 100 (available on <https://data.marine.copernicus.eu/products>). The assimilated SLA dataset includes along-track measurements from six of the seven operational nadir altimeters (CryoSat-2, HY-2B, Jason-3, Sentinel-3A, Sentinel-3B, and Sentinel-6A). The only difference with the operational conditions is that we exclude the altimeter AltiKa, to have an independent SLA dataset for validation. We use SWOT *ssha_filtered* variable from the L3_LR_SSH AVISO product, with a spatial resolution of 2 km. SWOT observations are additionally averaged and subsampled to a 6 km × 6 km resolution within the Mercator
 105 Ocean assimilation system, to match the model horizontal resolution and optimize computational efficiency.

In this study, we investigate the impact of SWOT data assimilation in two operational forecasting systems of the Copernicus Marine Service: (1) GLO12v4 (hereafter GLO12), the global forecasting system with a horizontal resolution of 1/12°, and (2) IBI36, the Iberian-Biscay-Ireland regional forecasting system with a horizontal resolution of 1/36°. These two configurations rely on the above-mentioned model and assimilation system but differ in their horizontal resolution and
 110 forcing, as IBI36 includes wind and tidal forcing that are not represented in GLO12. Beyond model configurations, we also compare the impact of the two SWOT orbits on the global simulation by assimilating data from both the Cal/Val (March to July 2023, 1 day repeat, ~10% spatial coverage with 28 tracks worldwide) and Science (September 2023 to present, 21-day repeat, global spatial coverage) phases.

Table 1 summarizes the OSEs analysed in this study, including the model configuration and simulation duration and
 115 period, and SWOT orbit and product version. For each OSE, two simulations are compared: a reference experiment without SWOT data assimilation and an experiment including SWOT data assimilation.

120 **Table 1: Summary of the OSEs analysed in this study, including the model configuration, SWOT orbit and product version, simulation period, assimilation duration, and spatial coverage of SWOT observations. Each OSE compares two otherwise identical simulations performed with and without SWOT data assimilation.**

OSE name	Model	SWOT orbit	SWOT version	Simulation duration and period covered
OSE_{Oper}	GLO12	Science	L3 LR v1.0.2	1 year 2023-09-06 to 2024-09-04
OSE_{CalVal}	GLO12	Cal/Val	L3 LR v2.0.1	3 months 2023-03-29 to 2023-07-10



OSE_{Science3m}	GLO12	Science	L3 LR v1.0.2	3 months 2023-09-06 to 2023-12-13
OSE_{IBI36}	IBI36	Science	L3 LR v1.0.2	8 months 2024-01-03 to 2024-09-04
OSE_{GLO12IBI}	GLO12 cut to IBI domain	Science	L3 LR v1.0.2	8 months 2023-09-06 to 2024-05-07

The different OSEs do not cover the same time periods, first because the two SWOT orbit phases did not fly at the same time, but also because of constraints associated with the various forecasting systems. We, however, designed the experiments to compare simulations after equivalent assimilation spin-up durations, to assess the impact of assimilating SWOT observations after approximately 3 months, 8 months, or 1 year of assimilation, depending on the experiment.

SWOT product versions are also not consistent between the Cal/Val and Science phase experiments due to the version available at the time the assimilation experiments were computed. The differences between these two versions include geophysical corrections (e.g. internal tide, sea state bias), data selection and editing. The scope of this study is to qualitatively assess and compare the response of the model to wide-swath data, which are not expected to be significantly affected by the version changes. Considering the computational resources required to run such experiments, the choice was made to use the material we had already computed.

Finally, all OSEs were conducted assuming SWOT data were instantaneously available, which does not reflect the operational reality, as processing SWOT products requires up to several days. Dedicated experiments have, however, been carried out to quantify the sensitivity of the assimilation gain to SWOT latency. While efforts are underway to deliver SWOT products within 48 hours, this question falls outside the scope of the present study. For this reason, as well, this study only assesses the models' analyses and not the forecast skills.

3 Validation of SWOT data assimilation in the global model

This section evaluates the impact of SWOT data assimilation on the global model performance. We use the simulations of OSE_{Oper} and OSE_{CalVal}, which are both based on the GLO12 configuration. We evaluate the effect on sea level anomaly and surface currents and then provide a detailed illustration to better understand the model response to wide-swath observations.

3.1 Global impact of SWOT data assimilation on model SLA

We first consider OSE_{Oper} and evaluate the impact of SWOT data assimilation on model SLA by comparing the model error variance against independent (i.e. not assimilated) AltiKa observations. This OSE has been designed to be representative of the changes expected in GLO12 following the addition of SWOT data to the operationally assimilated observations. The resulting error variances, with and without SWOT data assimilation, are shown in Fig. 1a, with the corresponding geographical distribution of the variance error reduction, computed in $2^\circ \times 2^\circ$ cells, shown in Fig. 1b. The first panel also reports the error variance for spatial scales below 100 km, obtained by applying a Gaussian spatial filter to both model and AltiKa nadir SLA observations.

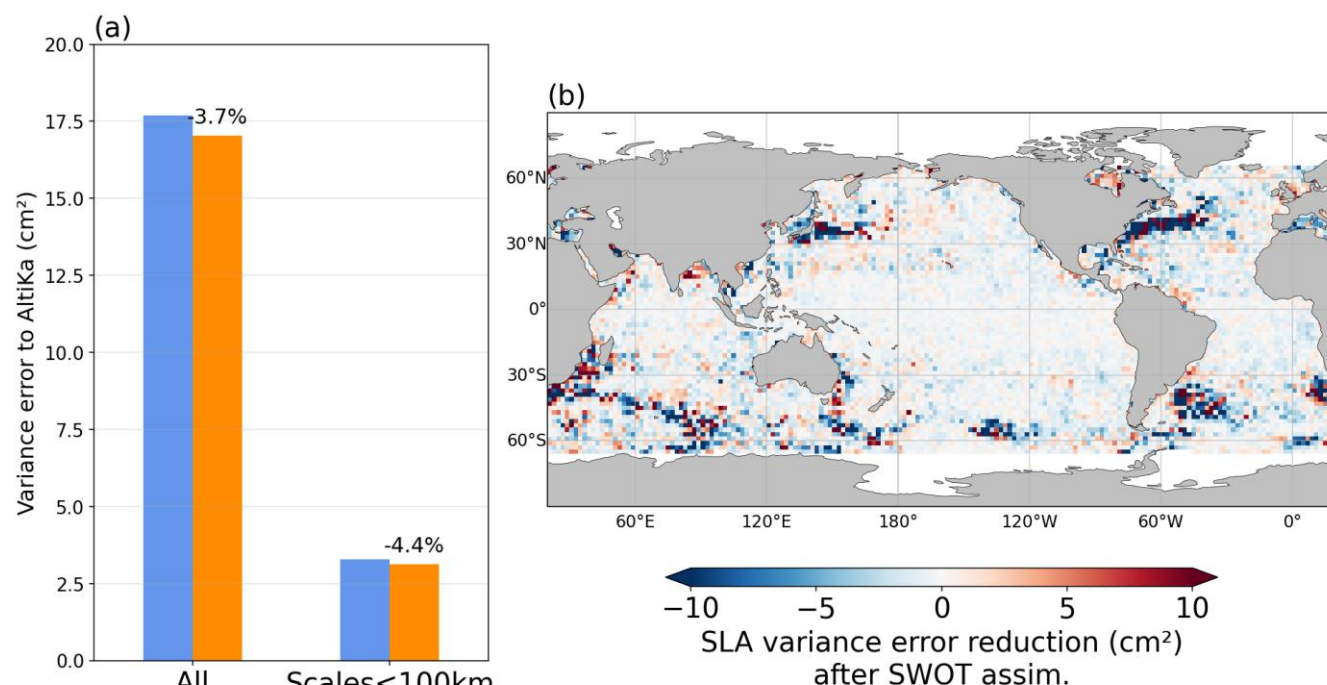


Figure 1: Evaluation of OSE_{Oper} SLA over one year (September 2023-September 2024). (a) Variance of the SLA error (cm²) relative to independent AltiKa observations for simulations without (blue) and with (orange) SWOT data assimilation, computed for the full SLA signal and for spatial scales below 100 km. The percentage gain from SWOT data assimilation is indicated above the orange bars. (b) Map of the SLA variance error reduction (cm²) relative to independent AltiKa observations, computed in $2^\circ \times 2^\circ$ cells.

Overall, SWOT data assimilation produces a positive impact on model SLA, reducing the error variance by 3.7% (0.7 cm²). The map shows that improvements are visible across all ocean basins, with the largest gains found in the most energetic regions, such as western boundary currents and the Antarctic Circumpolar Current (ACC). This spatial pattern is consistent with the behaviour of the data assimilation system, which adjusts the model state according to the misfits between model and observations. In regions of intense mesoscale activity, eddies and jets generate strong SLA signatures, and even small errors in the position or intensity of these structures can result in very large misfits. Consequently, SWOT observations



provide a stronger additional constraint in these regions. The gain is nevertheless not uniformly positive, with several regions exhibiting an increase in error variance following SWOT data assimilation. In some of them, such as the European Northwest Shelf, the Bay of Bengal, and the Amazon Shelf, the degradation appears spatially consistent, suggesting that it may reflect limitations in the model or in the assimilation strategy. In contrast, isolated degradations within western boundary currents may be more incidental and could result from the misrepresentation of individual structures during the simulation period. These localized degradations reflect the complex balance between model dynamics and the multiple observing systems contributing to the analysis. They nevertheless remain limited and globally outweighed by the improvements.

We also observe slightly larger gains at spatial scales below 100 km, which is encouraging given that one of the primary objectives of the SWOT mission is to improve the representation of mesoscale and fine-scale ocean dynamics (15 – 150 km) that are only partially resolved by conventional nadir altimetry and therefore less well constrained in models.

Although these domain and time averaged statistics mask larger local and episodic improvements, the overall gain remains more modest than those reported in the OSSEs of Tchonang et al. (2021) (30%) and the OSEs of Benkiran et al. (2026) (18%). This more limited improvement can be explained by several differences between their experiments and ours. First, both the OSSEs and the previous OSEs were conducted with only three assimilated nadir altimeters. Consequently, the reference state was less constrained than in the present six-altimeter configuration, and SWOT observations represented a proportionally larger contribution to the observing system. This is consistent with Le Traon et al. (2025), who showed that each additional assimilated altimeter improves model accuracy, but that the benefit progressively decreases as the number of assimilated altimeters increases. Second, the OSSEs relied on synthetic, idealized SWOT observations, whereas the present study assimilates real SWOT measurements that still contain residual instrumental errors and uncertainties in the geophysical corrections, reducing their effective impact on the analysis. The independent AltiKa observations used for validation also contain measurement errors, which may mask improvements in the model, particularly at small spatial scales and in coastal regions. Finally, the background error covariance used in the OSSEs was specifically tuned for the idealized configuration to maximize the assimilation benefit, whereas such optimal tuning is generally not achievable under real operational conditions.

3.2 Regional impact of SWOT data assimilation on model surface currents

The three-month Cal/Val phase has offered a rare opportunity to explore the smallest and fastest ocean signals and to exploit the synergy between in situ and satellite observations. The Adopt-A-Crossover (AdAC) Consortium coordinated the deployment of in situ platforms beneath SWOT crossovers, including drifters in California, Mediterranean Sea and Agulhas regions (Figure 2a), which we use here as independent validation datasets for OSE_{Cal/Val} surface currents. Surface currents are of particular interest for operational oceanography, as they are directly relevant to a wide range of operational activities and applications. This study also aims to highlight the value of local observations for global applications (here the validation of a global ocean model).



We employ both Eulerian and Lagrangian metrics, with correlation and mean separation distance respectively, to
195 obtain complementary information on the impact of SWOT data assimilation. Eulerian analyses compare drifter zonal and
meridional velocity time series with model fields interpolated at drifter positions and times, providing correlation statistics
for both current components. The Lagrangian analysis, in contrast, compares observed drifter trajectories with synthetic
particle trajectories advected in model current fields, yielding a direct measure of trajectory errors in kilometres, which is
particularly adapted to operational applications such as search and rescue or oil-spill response. A detailed description of the
200 drifter datasets, their processing, and the Lagrangian validation methodology is provided in Appendix A.

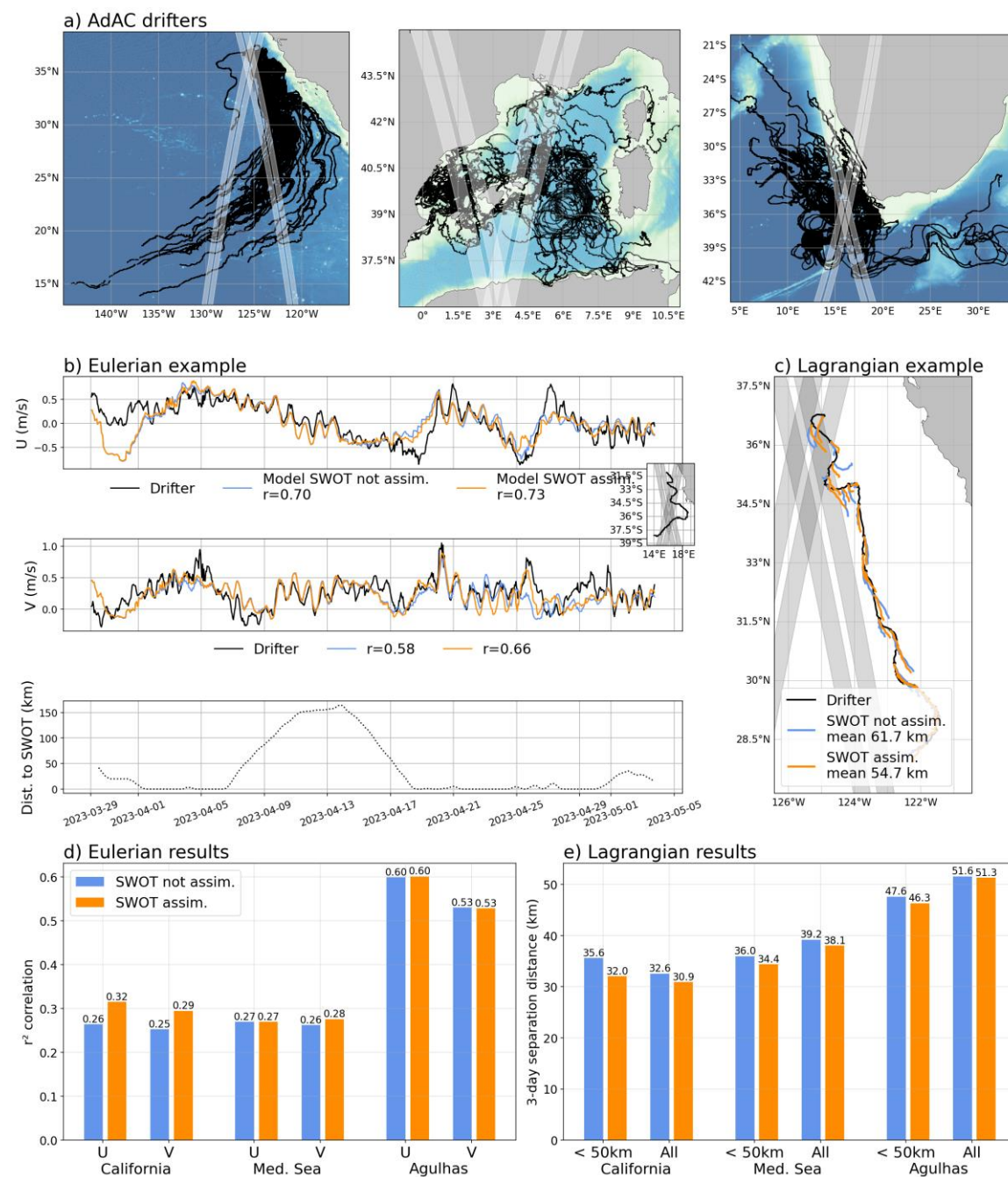


Figure 2: Validation of SWOT data assimilation against independent AdAC surface drifters. (a) Locations of the three drifter datasets used in this study: California Current, Mediterranean Sea, and Agulhas Current. (b) Example of the Eulerian validation for one drifter trajectory in the Agulhas Current. Time series of the zonal (top) and meridional (middle) surface current components measured by the drifter (black) and simulated by the model without (blue) and with (orange) SWOT data assimilation, interpolated at the drifter position and time. The bottom panel shows the distance between the drifter and the nearest SWOT swath. (c) Example of the Lagrangian validation for one drifter trajectory in the California Current. The observed drifter trajectory is shown in black, while the corresponding 3-day trajectories of virtual particles advected by the model without (blue) and with (orange) SWOT data assimilation are shown. (d) Eulerian results: Bar chart showing r^2 correlation for U and V components in California, Med. Sea, and Agulhas. (e) Lagrangian results: Bar chart showing 3-day separation distance (km) for < 50km and All categories in California, Med. Sea, and Agulhas.



210 and with (orange) SWOT data assimilation are overlaid. (d) Regional Eulerian validation, expressed as the coefficient of determination (r^2) between observed and modelled zonal and meridional surface current components. (e) Regional Lagrangian validation, expressed as the mean 3-day separation distance between observed drifter trajectories and modelled virtual particle trajectories.

Figure 2 presents examples of the Eulerian and Lagrangian analyses (Fig. 2b, c), together with the regional r^2 correlation scores and the mean 3-day separation distances (Fig. 2d, e).

215 The drifter time series example (Fig. 2b), in the Agulhas region, shows that the agreement between model and drifter currents is improved after SWOT data assimilation, for both the zonal and meridional components. It also reveals that when the drifter moves away from the SWOT swaths (up to 150 km from the satellite tracks around 2023-04-13), the two model versions produce nearly identical time series, indicating that SWOT data assimilation primarily affects regions within or close to the swaths during the Cal/Val phase. This behaviour is consistent with the spatial localisation used in SAM2, 220 which limits the influence of each assimilated observation to a defined radius around its location, effectively creating a local “bubble” of influence. This drifter was also deployed at a time close to the start of the simulation, and SWOT increments had not yet had sufficient time to propagate beyond the swaths.

The regional correlation scores confirm these observations. SWOT data assimilation improves surface current representation in both the zonal and meridional components across all three regions. This result is particularly significant as 225 it demonstrates the practical benefit of the instrumental transition from one-dimensional nadir to two-dimensional wide-swath altimetry. Indeed, OSSEs carried out at Mercator Ocean in the context of the ODYSEA mission, showed that nadir altimeters, likely due to their one-dimensional and meridional orientation, correctly constrain the zonal (U) current component but provide little to no constraint on the meridional (V) component (Isern-Fontanet et al., 2017; Mirouze et al., 2026). The two-dimensional mapping capability of SWOT therefore effectively addresses this limitation, simultaneously 230 constraining both current components.

The Lagrangian metric shows that SWOT data assimilation reduces the mean separation distance between observed drifters and simulated trajectories in all three regions, with the largest improvements occurring close to the SWOT swaths. This behaviour is illustrated by the California Current example shown in Fig. 2c. By improving the location and shape of mesoscale structures, SWOT data assimilation leads to more realistic advection pathways, allowing the virtual particles to 235 remain closer to the observed drifter trajectories. The reduction in mean separation distance is typically several kilometres, and its practical implications can be substantial for search-and-rescue or oil-spill applications, where the search area would be highly reduced.

Regional differences are, however, noteworthy. In the Agulhas Current, gains are relatively modest, as the dominant large-scale energetic dynamics of this western boundary current are already well constrained by the six-nadir altimeters assimilated. In contrast, the California Current shows the largest improvements, which reflects the capability of SWOT's 240 high resolution to better represent smaller mesoscale features in this less energetic eastern boundary current system, where nadir altimetry data assimilation provides weaker constraints due to its lower resolution. The California Current is also predominantly oriented southward, and as mentioned above, meridional current components are more difficult to constrain



with conventional nadir altimetry assimilation. The two-dimensional SWOT observations therefore appear to be particularly
245 valuable in this region.

3.3 Illustration of SWOT data assimilation impact

To further understand how SWOT data assimilation affects the model, and how wide-swath observations
complement the other assimilated data, we examine a specific example from the Mediterranean Sea during the Cal/Val
phase. Although this response is not representative of all situations or regions, it provides a clear illustration of the type of
250 impact that can be expected from the assimilation of wide-swath observations.

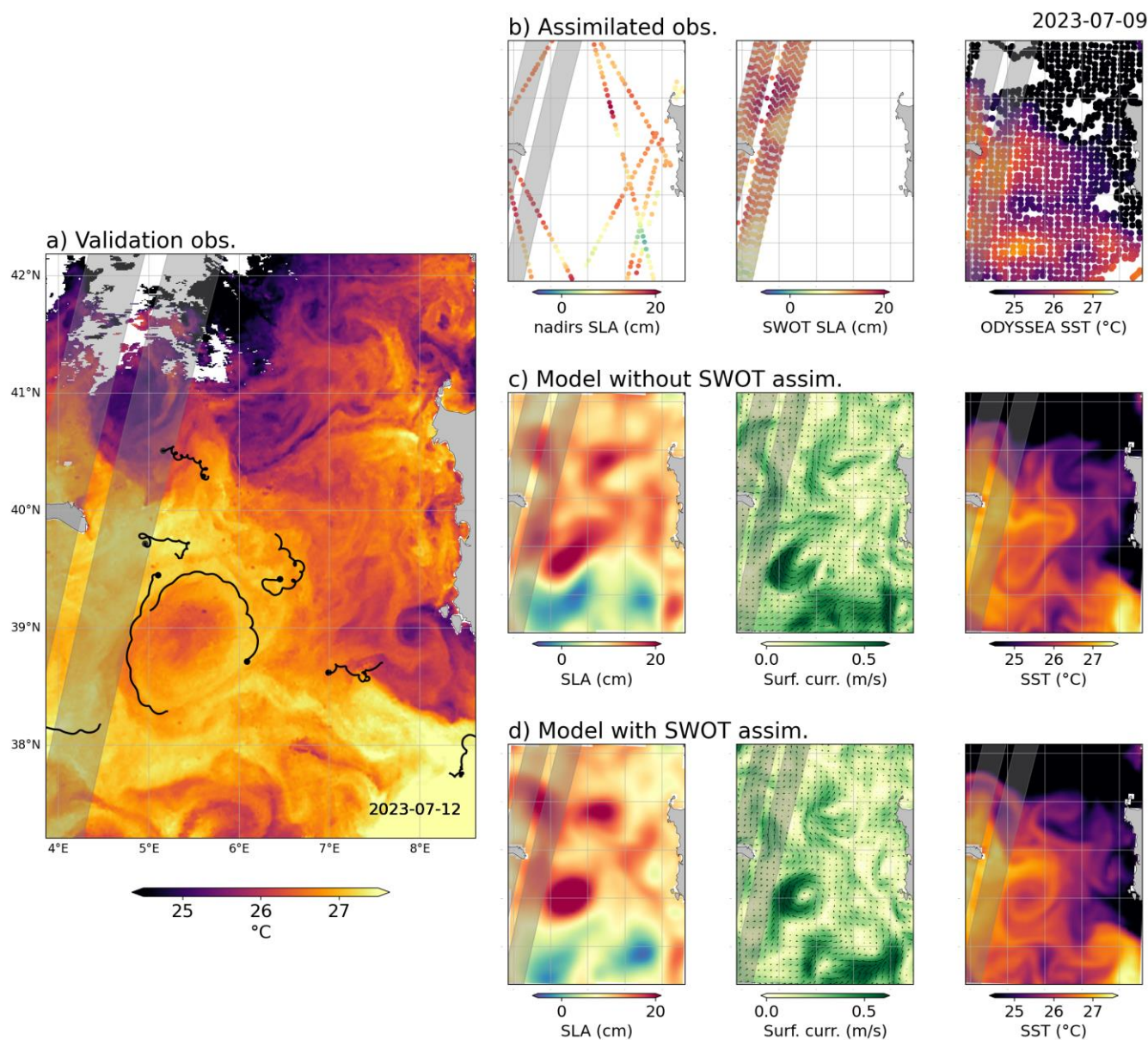


Figure 3: Impact of SWOT data assimilation on the representation of eddies on 9 July 2023 (end of Cal/Val phase). (a) snapshot of independent (not assimilated) SST from the Mediterranean Ultra High Resolution L3S product on 12 July 2023. Black dots indicate drifter positions on 9 July 2023, and black lines show their 7-day trajectories. (b) Assimilated observations, nadir SLA (left) on 9 July 2023 +/- 2 days, SWOT SLA (middle) and ODYSSEA SST on 9 July 2023. SST and nadirs are assimilated in both experiments. Model fields on 9 July 2023 in simulation without (c) and with (d) SWOT assimilated, SLA (cm, left), surface current magnitude (m/s, middle) and SST (°C, right). SWOT Cal/Val swaths are overlaid in gray.

Figure 3a shows the SST from a Copernicus Marine ultra-high-resolution satellite product, together with trajectories of surface drifters that were deployed during the SWOT Cal/Val phase (see Section 2.2) in the western Mediterranean Sea. Several mesoscale and submesoscale structures are visible, including two anticyclonic eddies parallel to the SWOT swath,



one of which entrained the drifter trajectories. These eddies, with characteristic diameters of 50-100 km, fall within the range of scales that SWOT was specifically designed to observe, making this case particularly illustrative. Figure 3c shows that, without SWOT data assimilation, these two anticyclonic eddies are poorly represented in terms of location and shape across all model variables (SLA, surface currents, SST) and become better represented following SWOT data assimilation. This case illustrates the potential for SWOT data assimilation to improve the representation of mesoscale and submesoscale features in terms of location, shape, and amplitude across all model surface variables. While such improvements are difficult to capture through global quantitative scores, they are of major importance for operational applications such as ship routing where even small positional errors in current structures can have significant practical consequences.

In this example, the marked improvement can be related to the distribution of other assimilated observations around the snapshot date. Figure 3b shows the nadir altimetry data available within ± 2 days of the snapshot date, together with the SST data available on that date. While the SST observations provide relatively complete coverage, the nadirs show gaps between the tracks, leaving the eddy region unsampled for several days. As a result, without SWOT data assimilation, the eddy structure progressively degrades and the two eddies begin to merge, whereas this evolution is corrected when SWOT observations are assimilated. It is worth noting that a nadir track crossed the eddies four days earlier, at which point both experiments represented the eddies correctly. This highlights the complementary role of wide-swath and nadir altimetry in maintaining the representation of mesoscale structures between nadir track crossings.

This result is also particularly encouraging because the eddies lie outside the SWOT Cal/Val swaths, demonstrating the capacity of the assimilation system to propagate SWOT information beyond the observed swaths and improve the model state in unsampled regions. It further suggests that wide-swath altimetry may provide stronger constraints on model dynamics than nadir altimetry, consistent with the findings of Benkiran et al. (2024), who demonstrated through OSSEs that a constellation of two wide-swath altimeters would outperform a constellation of 12 nadir altimeters.

Two small eddies west of Sardinia (near 8°E) also appear to be more accurately represented with SWOT data assimilation. It is possible that improving the position of larger-scale structures contributes to a better representation of smaller-scale features. However, local improvement at such small scales (~ 25 km) may also reflect chaotic or stochastic model behaviour rather than a direct dynamical response to SWOT data assimilation and should therefore be interpreted with caution.

4 Impact of model configuration and satellite sampling

Having established the benefits of operational SWOT SLA assimilation, we now examine how these benefits depend on both the model configuration and the satellite sampling strategy. We first compare the OSEs using the SWOT Cal/Val and Science orbits to assess the relative importance of spatial coverage and revisit frequency for the assimilation system. We then compare SWOT data assimilation in the global $1/12^{\circ}$ GLO12 and regional $1/36^{\circ}$ IBI36 configurations.



Beyond the difference in horizontal resolution, these configurations also differ in their physical representation: IBI36 explicitly accounts for atmospheric pressure forcing and tides, whereas these processes are not represented in GLO12.

4.1 Spectral response to SWOT data assimilation

295 We begin the comparison of model configurations and satellite sampling by investigating the spatial scales at which the model is modified by SWOT data assimilation using wavenumber spectra. Figure 4 shows the power spectral density (PSD) of model SLA, together with the PSD of the SLA difference between experiments with and without SWOT data assimilation. The model SLA spectra describe the distribution of SLA variance across spatial scales, while the spectra of the SLA differences identify the scales at which the model is most strongly modified by SWOT data assimilation. This analysis
 300 therefore provides information on the spatial scales affected by SWOT data assimilation but does not indicate whether these changes are associated with improvements in the model accuracy.

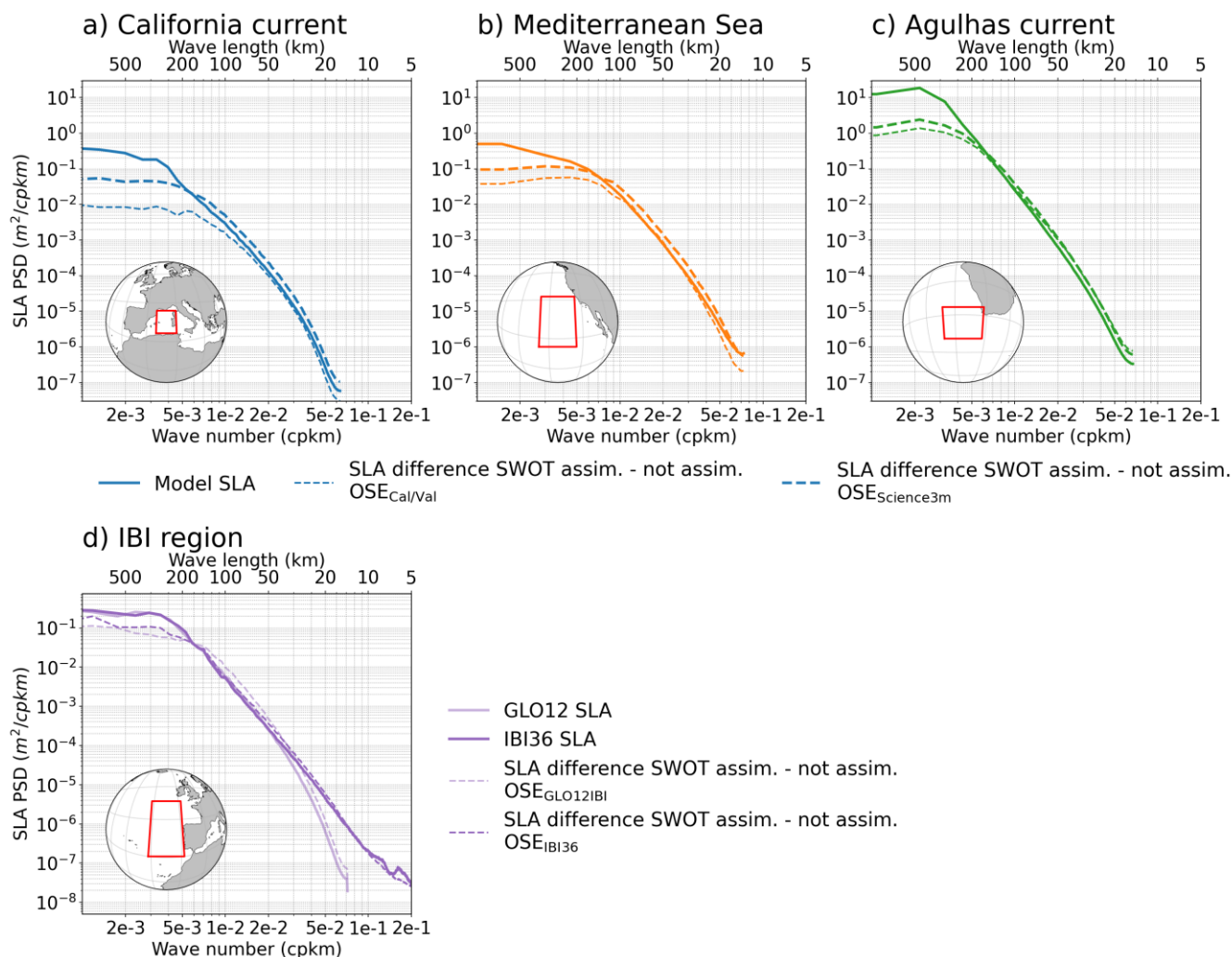




Figure 4. Wavenumber power spectral density of model sea level anomaly (SLA, solid lines) and of the SLA difference between simulations with and without SWOT data assimilation (dashed lines) for the (a) California Current, (b) Mediterranean Sea, (c) Agulhas Current, and (d) IBI regions. Dashed lines represent the power spectral density of the SLA difference for OSECal/Val (thin dashed lines) and OSEScience3m (thick dashed lines) in panels (a–c), and for OSE GLO12IBI and OSEIBI36 in panel (d). Spectra are computed along the model grid meridional direction using each model native grid.

We perform this analysis over the three regions considered in the surface current validation, as well as over the IBI domain. The California Current, Mediterranean Sea, and Agulhas Current are of particular interest because they represent three contrasting dynamical regimes. The California Current is an eastern boundary upwelling system (Hickey and Royer, 2001); the Mediterranean Sea is a semi-enclosed basin characterized by sub-basin-scale dynamics and dense-water formation (Milot and Taupier-Letage, 2005); and the Agulhas Current is one of the most energetic western boundary currents in the global ocean (Beal et al., 2011). These three regions are also located beneath SWOT Cal/Val crossovers, making them more suitable for comparing the Cal/Val and Science experiments.

The model SLA spectra differ substantially between regions, reflecting their contrasted dynamical activity. The Agulhas Current exhibits the highest energy over nearly all spatial scales, whereas the California Current contains substantially less mesoscale energy in the model.

The spectra of the assimilation-induced differences perfectly match the SLA spectra for scales below 200 km, with stronger responses in more energetic regions. This indicates that the effects of SWOT data assimilation are not restricted to a specific range of spatial scales but can modify the model down to its smallest ones resolved. Above 200 km, the difference spectra are less energetic than the SLA field itself, indicating that the large scales are less affected. This is expected, as SWOT data are not intended to substantially constrain the large-scale circulation, which is already well observed by nadir altimeters and the model mean dynamic topography. The SLA difference spectra also indicate that the changes share the same wavelengths as the original SLA field, meaning that assimilation neither adds nor removes energy at any given spatial scale. In other words, the structures in the two versions have similar characteristic scales, and SWOT assimilation only modified their location and geometry.

In the three regions, the PSD of SLA changes from OSE_{Science3m} are higher than OSE_{Cal/Val} over almost the entire range of resolved wavelengths. This indicates that the broader spatial coverage of the Science orbit leads to a stronger overall response to SWOT data assimilation than the higher revisit frequency of the Cal/Val orbit.

Figure 4d compares the spectra from OSE_{GLO12IBI} and OSE_{IBI36} and therefore assesses the influence of model configuration on SWOT data assimilation impact, in the IBI region. The SLA spectra are nearly identical down to wavelengths of approximately 45 km, below which the higher-resolution IBI36 configuration contains substantially more energy than GLO12. This result suggests that both the finer grid spacing and the representation of physical processes absent from GLO12, such as tides and atmospheric pressure forcing, contribute to the additional small-scale variability resolved by IBI36. This interpretation is consistent with Fouchet et al. (2025), who attributed the mismatch between GLO12 and SWOT spectral slopes to the model's coarser resolution and the absence of high-frequency processes.



340 The spectra of the assimilation-induced differences closely follow those of SLA in the IBI region as well. They are therefore very similar between the two configurations down to wavelengths of approximately 45 km, whereas at smaller scales the assimilation-induced changes are substantially larger in IBI36 than in GLO12. This indicates that SWOT data assimilation produces a similar response at scales larger than approximately 45 km in the two configurations, while the effect at small scales is much stronger in IBI36 than in GLO12.

4.2 Comparison of assimilation performances

345 Having characterized the spatial scales affected by SWOT data assimilation in the different OSEs, we now assess how these changes translate into an improvement in model SLA relative to independent AltiKa observations.

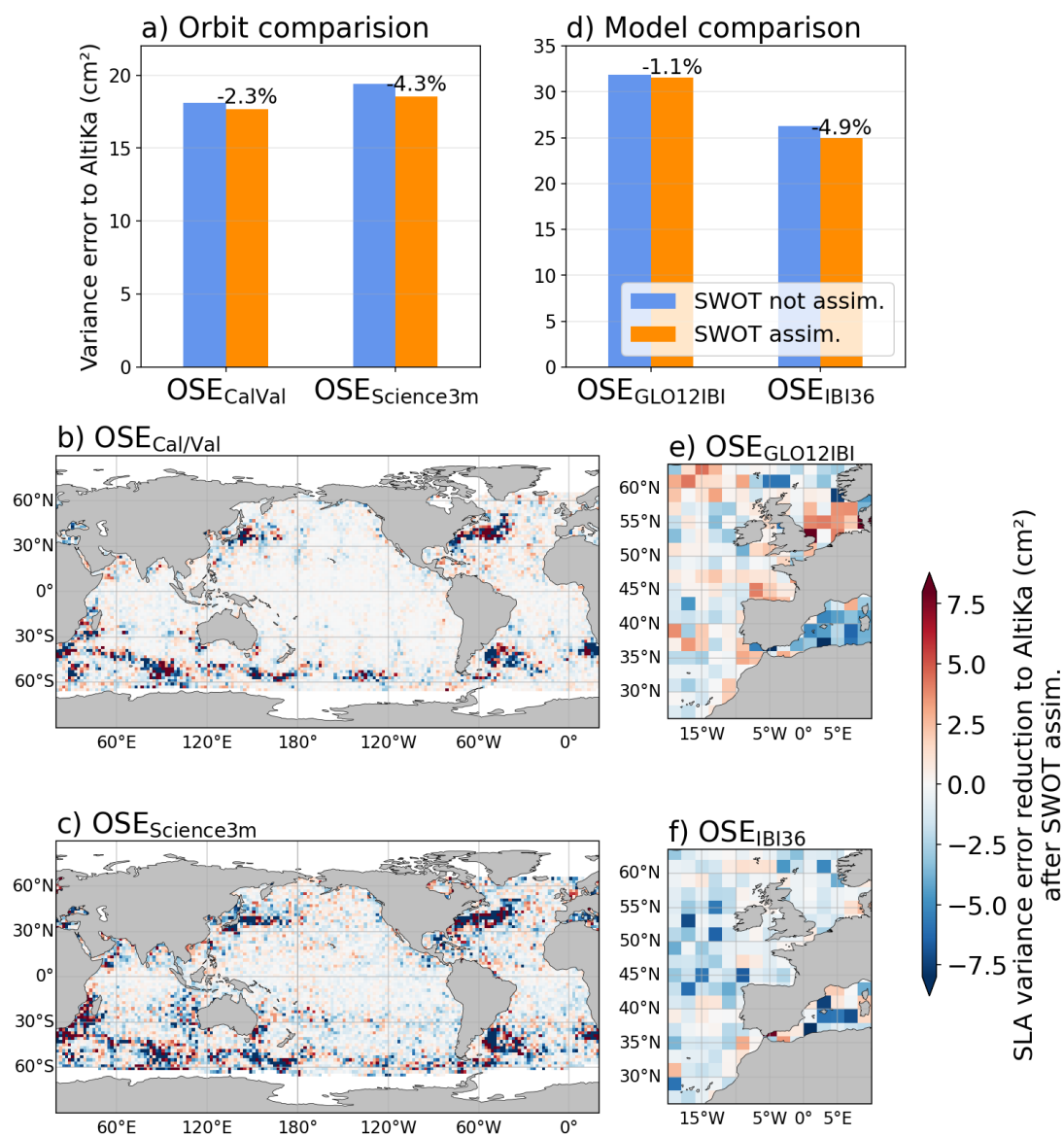


Figure 5: Comparison of the impact of SWOT data assimilation for different SWOT orbits (a–c) and model configurations (d–f). (a, d) SLA error variance (cm²) relative to independent AltiKa observations for simulations without (blue) and with (orange) SWOT data assimilation, computed over the full model domain for OSE_{CalVal} and OSE_{Science3m} (a), and for OSE_{GLO12IBI} and OSE_{IBI36} (d). The percentage gain from SWOT data assimilation is indicated above the orange bars. (b, c, e, f). Geographical distribution of the SLA error variance reduction following SWOT data assimilation, computed in $2^\circ \times 2^\circ$ cells for OSE_{CalVal} and OSE_{Science3m} (b, c), and for OSE_{GLO12IBI} and OSE_{IBI36} (e, f). Blue indicates a reduction in SLA error variance following SWOT data assimilation.

Figure 5 compares the SLA error variance relative to independent AltiKa observations for simulations with and without SWOT data assimilation, quantifying the assimilation benefit for the two satellite sampling strategies and the two



model configurations considered in this study. The maps further show the geographical distribution of the error variance reduction, highlighting the regions where SWOT data assimilation provides the largest improvements.

The first comparison (Fig. 5a–c) focuses on the SWOT Cal/Val and Science orbits, using OSE_{CalVal} and $OSE_{Science3m}$, respectively. Panel (a) shows the SLA error variance relative to independent AltiKa observations, with and without SWOT data assimilation. The global statistics show that, for a three-month assimilation period, the assimilation of the Science orbit data provides a larger reduction in SLA error variance than the Cal/Val orbit, with gains of 4.3% and 2.3%, respectively. The geographical distributions of the error reduction (Fig. 5b, c) show that the largest gains occur in energetic regions in both experiments. In the Cal/Val experiment, larger gains are also visible beneath the SWOT swaths, reflecting the high temporal sampling provided by the daily revisit, and at crossover locations where the swaths intersect. However, improvements also extend beyond the swaths, particularly in highly energetic regions, indicating that the information provided by SWOT can propagate horizontally.

Although the global gain is smaller for OSE_{CalVal} than for $OSE_{Science3m}$, the Cal/Val experiment produces locally comparable or even larger reductions in error variance at several crossover locations, such as near 180°W, 30°N, off California, and in the northeastern Atlantic. These local gains illustrate the benefit of the daily revisit provided by the Cal/Val orbit, which allows SWOT observations to repeatedly constrain the same locations over the assimilation period. At the global scale, however, the broader spatial coverage of the Science orbit results in a larger overall improvement. This indicates that, for the present assimilation system, broad spatial coverage has a greater influence on the global assimilation performance than the higher revisit frequency of the Cal/Val orbit.

The second comparison focuses on the global GLO12 and regional IBI36 model configurations over the IBI domain, using $OSE_{GLO12IBI}$ and OSE_{IBI36} (Fig. 5d–f). Panel (d) shows the corresponding SLA error variance relative to AltiKa, while panels (e) and (f) show the geographical distribution of the error variance reduction for GLO12 and IBI36, respectively. The reduction in SLA error variance reaches 4.9% for IBI36, compared with only 1.1% for GLO12. The spatial distributions also differ substantially, with IBI36 showing a more widespread and homogeneous reduction in SLA error variance across the IBI domain, whereas the gains in GLO12 are weaker and more localized.

Taken together with the spectral analysis, these results indicate that the higher-resolution IBI36 configuration can extract substantially more benefit from SWOT observations. This suggests that model resolution and/or the representation of physical processes (tides and winds) may influence the effectiveness of SWOT data assimilation. However, the present experiments do not allow to separate the respective contributions of resolution and physical content.

Overall, the results show that the assimilation system benefits from observations combining broad spatial coverage with frequent sampling. The assimilation of the Science orbit data provides a larger global benefit through its broad coverage, while the high revisit frequency of the Cal/Val orbit produces strong local improvements at the repeatedly sampled locations. This supports the interest of future altimetry constellations combining wide-swath coverage with improved revisit periods, such as the Sentinel-3 Next Generation Topography (NGT) mission, which is designed to combine two wide-swath altimeters. On the model side, the stronger benefit obtained with IBI36 highlights the importance of developing higher-



390 resolution models and improving the representation of physical processes to fully exploit the information provided by SWOT.

5 Conclusion

The SWOT mission represents a major advance for oceanography and for operational oceanography. Its ability to provide high-resolution two-dimensional observations of sea surface height offers new opportunities to improve the representation of mesoscale and fine-scale ocean dynamics in operational analysis and forecasting systems.

In this study, we evaluated the impact of assimilating real SWOT observations into the Mercator Ocean operational system under realistic observing conditions. Overall, SWOT data assimilation improves the model representation of sea level and surface currents. At the global scale, the reduction in SLA error variance demonstrates a measurable improvement in model performance. Surface currents are also improved following SWOT data assimilation, as demonstrated for the Cal/Val phase experiments, using independent AdAC drifter validation observations. In particular, SWOT data assimilation improves the representation of both the zonal and meridional current components, providing a more balanced constraint on surface circulation than conventional nadir altimetry. Although this validation was only possible during the Cal/Val period, the results obtained with Science phase data suggest that these benefits can also be expected under the future operational use of SWOT.

The detailed example presented in this study further illustrates the ability of SWOT observations to improve the representation of the geometry of mesoscale structures, including their position, shape, and intensity. However, assessing such improvements remains challenging using variance error metrics alone. More specific metrics designed to evaluate the geometry of mesoscale features would therefore be needed to quantify this aspect of the SWOT contribution more precisely. In that sense, high-resolution SST observations could provide a valuable independent dataset for this purpose, as they offer complementary information on the location and geometry of mesoscale features.

The benefits of assimilating SWOT data are nevertheless relatively modest at the global scale and are not spatially homogeneous. As previously mentioned, SWOT is part of a large observing system with many altimeters already in operation and its temporal sampling remains an inherent limitation for operational systems. Fully exploiting the information provided by SWOT will require both higher model resolution and improved data assimilation methods. While the validation presented here focuses on surface variables, we performed additional evaluations using independent XBT temperature profiles to assess the impact of SWOT data assimilation throughout the water column. These results (not shown) were consistent with the surface validation, showing an overall slight improvement in model performance, stronger in energetic regions, but with a spatially heterogeneous response and localized degradations.

The comparison of different SWOT sampling strategies and model configurations provides insights into how the three components of operational oceanography (namely observations, models, and data assimilation) could further benefit from the information provided by wide-swath altimetry.



From an observing system perspective, our results highlight the importance of combining broad spatial coverage with frequent revisit times. The assimilation of SWOT Science phase data provides a larger global benefit than that of the Cal/Val phase, which supports the development of future altimetry missions with wide-swath altimeters having improved temporal sampling, such as Copernicus Sentinel-3 Topography Next Generation two satellite constellation.

From a modelling perspective, our results highlight the importance of developing operational models with resolution and physical representation consistent with the physical content of new observing systems. The higher-resolution IBI36 configuration derives substantially greater benefit from SWOT data assimilation than GLO12, with a stronger response at smaller spatial scales. Beyond horizontal resolution, our results also highlight the potential importance of the physical processes represented by the model. In particular, the explicit representation of tides in IBI36 may help the assimilation system better account for high-frequency signals present in SWOT observations, including non-phase-locked internal tides. Recent results from Yadidya et al. (2026) show that a substantial part of incoherent internal tides can be predicted when the evolving three-dimensional ocean state and tidal forcing are explicitly represented. Although the respective contributions of model resolution and physical content are not separated in our experiments, these results suggest that an accurate representation of tides and internal wave dynamics may be an important prerequisite for fully exploiting SWOT observations at small spatial scales.

Finally, data assimilation methods themselves will need to evolve to efficiently exploit increasingly dense and high-resolution observations such as those provided by SWOT (Martin et al., 2025). Wide-swath observations are affected by spatially correlated observation errors, which we mitigate here by subsampling the data and assuming that the resulting observations are uncorrelated. However, many studies have demonstrated the benefits of accounting for spatial correlations in observation errors within data assimilation systems (e.g., Ruggiero et al., 2016, and references therein). Approaches accounting for these correlations are still being investigated (e.g., Goux et al., 2025) but remain computationally costly for operational systems. Machine learning methods, on the other hand, are being investigated for different components of data assimilation, from data processing to analysis and post-processing. Grande et al. (2026) discuss several approaches, including surrogate models, autoencoders, physics-informed neural networks, and latent-space data assimilation, and emphasize the need for hybrid systems that combine physical constraints with machine-learning methods. Such developments are already underway at Mercator Ocean, with some approaches already being implemented operationally (e.g. El Aouni et al., 2025). Other research and development activities include ensemble methods, which represent the ocean state through a set of forecasts that provide an estimate of the range of possible future states and a forecast uncertainty. Such ensemble methods have already become a key component of weather and climate prediction systems and are increasingly being explored for ocean forecasting (Hoteit et al., 2025). Finally, the ability to distinguish balanced circulation from non-balanced, high-frequency signals remains an important challenge for operational assimilation systems (Bellemin-Laponnaz et al., 2026). Several recent studies have explored new approaches specifically designed to better exploit wide-swath altimetry, such as scale separation methods, that aim to better exploit observational information across the different spatial scales of ocean variability (e.g. Tissier et al., 2019; Wang et al., 2026).



Continued improvements in the quality of SWOT observations, the accuracy of ocean models, and data assimilation techniques shall then further enhance the benefits that can be achieved from SWOT data assimilation.

Appendix A : AdAC drifter study

460 **Drifter data sources** The California Current dataset comes from the S-MODE (Sub-Mesoscale Ocean Dynamics Experiment) campaign (Farrar et al., 2025). A total of 137 surface drifters, deployed from 4 April 2023 onward, were retained for this study.

The Mediterranean dataset is taken from Demol et al. (2025) and consists of Lagrangian surface drifters deployed in the western Mediterranean Sea during the C-SWOT-2023, BioSWOT-Med, and FaSt-SWOT campaigns. To ensure consistency
465 with the model outputs and with the other study regions, only drifters drogued within the upper metre of the water column (CODE, CARTHE, and HEREON types) were considered. The final dataset comprises 90 drifters covering the period from 28 March to 5 October 2023.

Finally, the Agulhas dataset originates from the QUICCHE (QUantifying Interocean Fluxes in the Cape Cauldron Hotspot of Eddy Kinetic Energy) campaign (Novelli and Beal, 2025). It consists of CARTHE surface drifters drogued at 0.6 m depth.
470 Because the campaign began several weeks before SWOT entered its scientifically exploitable Cal/Val phase, many drifters had either completed their trajectories or only a short portion of their trajectories overlapped with the analysis period. Consequently, 198 drifters were retained for the present study.

Drifter processing AdAC drifter positions are provided at hourly intervals. Although some of the datasets also include
475 current estimates, we recomputed surface velocities using the same processing method for all three regions to ensure consistency. The differences between the velocities computed here and those provided with the original datasets were found to be negligible. Outlier positions were first removed by applying a five-point median filter to the longitude and latitude time series, following the methodology of Tranchant et al. (2025). Surface velocities were then computed from the filtered positions using a central differencing scheme, following Coadou-Chaventon et al. (2025). Finally, all trajectories and time
480 series were visually inspected to ensure that the processing efficiently removed remaining inconsistencies. Drifter observations contain high-frequency motions, including near-inertial oscillations and tidal signals, which were intentionally retained for the comparison with the model. Unbalanced motions were likewise not filtered out.

Parcels simulations Model surface currents have been validated against drifter data comparing drifters' observed
485 trajectories to synthetic trajectories computed from model current fields. We use the Parcels v2.0 (Delandmeter and van Seville, 2019) particle tracking software to simulate the trajectories, advecting Lagrangian particles through the Eulerian velocity field. As previously mentioned, model currents were augmented with the surface tidal and Stokes drift components



using the Copernicus Marine SMOC product, so as to match the displacement physical content of drifters as closely as possible. Particles have been seeded at every hourly position of drifter trajectories and followed for 3 days (sensitivity tests proved 3 days to be the most relevant period to compare the three studied regions).

Lagrangian metric Lagrangian particle-tracking studies are often used to compare current products with drifters and include a wide range of metrics such as Finite-Size Lyapunov Exponent (FSLE; e.g. Siegelman et al. (2020)), or skill scores (Liu and Weisberg, 2011). Here we use the mean Lagrangian separation distance, defined as the separation distance between the end points of the simulated and observed Lagrangian trajectories, 3 days after being seeded at the same location. This choice has been motivated by the need for a more practical metric, in km, more relevant in operational oceanography and applications such as pollutant dispersion or search and rescue.

Code and data availability

Validation drifter datasets were obtained from Demol et al. (2025), Farrar et al. (2025) and Novelli and Beal (2025); the SST validation dataset comes from the E.U. Copernicus Marine Service Information: DOI:10.48670/moi-00171.

The numerical model simulations generated in this study consist of multi-month four-dimensional model fields from five experiments, with two simulations for each experiment (with and without SWOT data assimilation). Due to the large volume of these data, the full model output is not publicly available but will be provided by the authors upon request. If required by editors or reviewers, the datasets containing model and AltiKa SLA values at AltiKa observation locations can be made available.

Author contributions

EF designed the assimilation experiments, developed the validation diagnostics and conducted the analyses, and wrote the manuscript. MB ran the assimilation experiments in the global model, RE ran the assimilation experiments in the regional model, contributed to the analysis of the results and edited the manuscript. PYLT supervised the studies and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.



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